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FATIGUE FAILURE AT CONTACT SURFACES OF HOT-ROLLED GEAR-TOOTH TRAIN

[Comment: The following article by A. D. Kuz'min and N. V. Vasil'chikov, Candidates of Technical Sciences, and Yuri M. V. Barbarich appeared in the Moscow monthly periodical Vestnik Mashinostroyeniya, No 3, March 1955.

Figures mentioned in the text are appended to the report.

The USSR has developed and has introduced into industry a new method of producing gears by means of rolling heated blanks through toothed cylindrical dies. This method greatly simplifies the mass production of gears. To date, approximately 50,000 rolled gears have been produced and have withstood the test of time in use. However, since the method is still very new, certain basic data on the gear-tooth design and mechanical characteristics are still lacking. The assumption that hot rolled gears, having had teeth pressed into contour by mating teeth, would be able to withstand greater loads than gears with machined teeth, has not as yet been proven a fact, due to insufficient experience.

In studying the microstructure of the cross-section of the teeth formed by hot rolling (Figure 1), it is confirmed that the outer surface of the tooth has a layer of refined metal. This layer is about 0.5-0.6 mm in thickness. The grain size gradually increases in proportion to the distance from the surface of the tooth to its center. The general grain of the metal conforms with the contour of the tooth.

This article presents briefly the results of research performed by the authors at the Central Scientific Research Institute of Technology and Machine Building, the purpose being to compare data on the contact fatigue of hot-rolled gears versus machined gears.

The hot-rolled gears and the machined gears were tested in the same setup and under identical conditions. The testing setup consisted of a single-stage reduction gear train, using the experimental gears (Figure 2); a Prony Brake and an AC prime mover ($N = 12$ kw, $n = 1460$ rpm). The direction of gear rotation and the oil level in the gear box was maintained constant during the period of the experiment. The type of oil used was the same (machine T); its operating temperature was maintained between 33° and 35°C, and it was replaced with fresh oil after every 80-90 hours of use.

The gears tested, both the driving and the driven, were made out of grade 45 steel, having the following chemical composition: 0.43% C; 0.26% Si; 0.60% Mn; 0.02% S; 0.035% P. The 45 steel was selected because it is widely used for the manufacture of industrial gear transmissions, and because the known data on the fatigue crumbling qualities of this steel would make it possible to evaluate correctly the results obtained in this experiment. Both the large and the small gears were formed by the hot-rolled process with the following production specifications:

	<u>Small Gear</u>	<u>Large Gear</u>
No of teeth per gear (z)	30	70
Module of gear (m)	2	2
Rpm (during rolling)	90	135

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	<u>Small Gear</u>	<u>Large Gear</u>
Feed of blanks in mm/revolution	0.3-0.5	1.3-0.5
Temperature of blanks in °C		
Start of rolling operation	1050	1050
End of rolling operation	650-750	750-800

The rolled blanks (Figure 3) were air cooled at room temperature and were not subjected to further heat treatment. The only machining process performed to produce the rolled gears consisted of cutting the rolled blanks into gears and boring the mounting center hole. The finished gears are shown in Figure 4.

The machined gears were produced out of the same forging as were the rolled ones. The milling was done on a gear cutting of the "Komsomolets" type. The dimensional limits of the milled gears were in the 2nd-3rd accuracy class. The hot-rolled gears were in the 3rd-4th accuracy class.

Imperfect mating of the gears creates additional dynamic stresses and loads on the gears during their operation. To eliminate the influence of this factor, the rolled gears were machined to bring them up to the accuracy standards of milled gears (0.15 mm of metal was removed from the contact surfaces of the rolled gear teeth).

The uniformity of the working surfaces of the gear teeth was measured by means of a comparison microscope of the "MIS-11" type. The average height of the irregularities of the milled gears was found to be 10-11 microns (5th class). The rolled gears, which were finish-machined, had an average height of irregularities measuring 8 microns (6th class). The uniformity of the tooth surfaces has a great influence on the fatigue strength of these surfaces, and therefore the milled gear teeth were lapped to the standards of uniformity of the rolled gear tooth surfaces, to make all things equal for experimental purposes.

The rolled gears were found to have a hardness of 200-220 Brinell. In order to have an equal hardness rating for both types of gears, the gear blanks that were to be milled were normalized.

The point of initial surface fatigue failure of the teeth was determined with the start of their progressive crumbling. If any crumbling at all was noticed on the surface of the teeth, but did not progress further, it was not considered as the point of initial fatigue failure. At the time that initial crumbling developed into progressive crumbling, and eventually led to the destruction of the tooth contour (Figure 5), it was assumed that surface fatigue failure had been reached. The number of cycles under load at this point, when the progressive crumbling first started, was accepted as a coordinate point on the fatigue curve graphs.

The maximum specific pressure at the field of contact was calculated by the formula:

$$\sigma = \sqrt{\frac{1}{b} \cdot P_1 P_2 \frac{P_1 + P_2}{(K_1 + K_2) \pi^2}}$$

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where P = load

b = length of contact

ρ_1 & ρ_2 = radii of curvature of cylinders at the point of contact

$$K_1 = \frac{1 - \mu_1^2}{\pi E_2}$$

Here μ_1 and μ_2 are Poisson's coefficients.
 E_1 and E_2 are moduli of elasticity of the metals.

$$K_2 = \frac{1 - \mu_2^2}{\pi E_1}$$

As a result of the experiments the fatigue failure limit of milled gears was determined to be $P_k = 53 \text{ kg/mm}^2$ (Figure 6, Curve 1). This is completely confirmed by data previously obtained by G. K. Trubin ($P_k = 55 \text{ kg/mm}^2$) through similar experimentation. The fatigue failure limit for the hot-rolled gears was found to be higher, being $P_k = 70 \text{ kg/mm}^2$ (Figure 6, Curve 2).

The characteristics of the destruction of the tooth surfaces was studied through the use of polished microsections. Figure 7a is a photograph of a milled tooth surface showing the formation of a crack. Figure 7b shows a pit which resulted from the crumbling of the surface of a milled tooth. In Figure 7c and 7d, the formation of a crack and a crumbling pit, on the surface of a rolled gear tooth, are shown respectively.

In comparing the characteristics of the surface destruction of milled gear teeth and the hot-rolled ones, it can be noted that in the case of the milled gears the cracks spread from the surface inward, into the body of the tooth, whereas in the hot-rolled gears the cracks form at a small angle to the surface or parallel to it, and conform to the grain of metal.

In connection with this different formation of cracks, it is observed that there is a relationship in the character of pits formed on crumbling. In the milled gear teeth the pits are small on the surface but are deep. In contrast, the pits on rolled gear teeth are shallow, but are much larger on the surface.

As was mentioned previously, the teeth of the rolled gears were finish-machined, prior to their use in this experiment, by the removal of 0.15 mm from their surface. This was done in order to make their pitch exactly the same as that of the milled gears. However, considering the fact that hot-rolled gears are being used in the field without this finish machining of their tooth contour, it was interesting to test them as they were, after the rolling process only. This special test showed that the unfinished hot-rolled gears have a fatigue failure limit of $P_k = 42 \text{ kg/mm}^2$. The graph in Figure 3 shows the fatigue crumbling curve in this case.

Therefore, the surface compression, or grain refining, of gear teeth which is achieved by the plastic deformation (this process being unique to the hot-rolled method), considerably increases the resistance of the teeth to fatigue failure. Rolled gears, and also rolled gears which have been finish-machined for desirable tooth contours, possess much higher qualities of resistance to fatigue failure than the milled gears produced out of the same material.

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Rolled gears with unfinished gear teeth, regardless of their low standards of mating (4th class), and although some surface imperfections are present, do however, have a sufficiently high level of surface fatigue failure rate are absolutely acceptable for use in the building of machinery.

[Appended Figures Follow:]

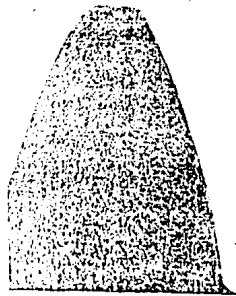


Fig 1. Hot-Rolled Tooth
50X Magnification

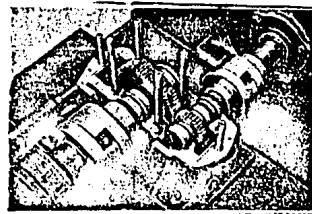


Fig 2. Single-Stage Reduction
Gear Train With Experi-
mental Gears



Fig 3. Rolled Blanks

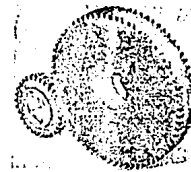


Fig 4. Finished Gears

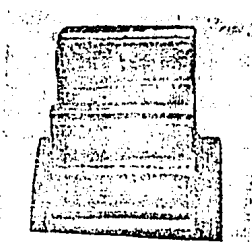


Fig 5. Destruction of Tooth Contour

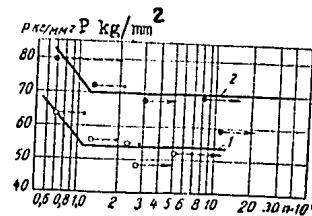


Fig 6. Number of Cycles

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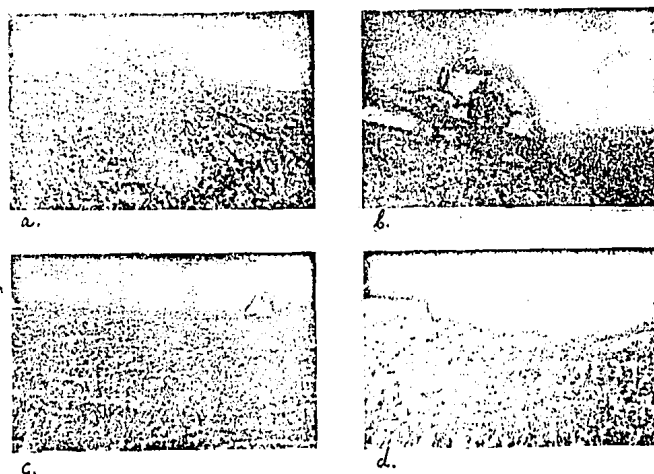


Fig 7. Destruction of Tooth Surfaces. 135X Magnification

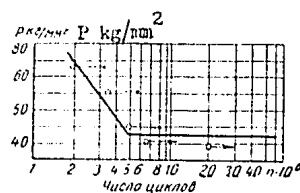


Fig 8. Number of Cycles

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- 5 -